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Vibrations of Metal Web Joist Timber Floors with Strongbacks

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Abstract

This research aims to assess the effects of joist spacing, strongbacks and ceiling on the dynamic response of the timber floors with metal web joists so as to evaluate the vibrational design criteria, e.g. modal frequencies, modal shapes, damping and unit point load deflection, required by EC5-1-1 and the UK NA for timber floors. In general, joist spacing, strongbacks and ceiling do not largely influence the fundamental frequency and damping ratio, but affect higher modal frequencies. The measured damping ratio for the fundamental mode is 0.86% on average. The use of strongback considerably reduces the number of first order modes below 40 Hz, and causes easier fulfilment of velocity design criterion. The test results indicate that the decrease in joist spacing, the increase in number, size and stiffness of strongbacks, and the use of ceiling all largely reduce the maximum displacement of the floors. On average, the calculated displacements based on the equations in the UK National Annex are close to those measured.

Keywords chosen from ICE Publishing list
Codes of practice & standards; Dynamics; Timber structures.

List of notations

a	design limit of the deflection of the timber floor under unit point load (mm/kN)
a_{rms}	root-mean-square acceleration
$a_{w,95}$	95% fractile weighted acceleration
B	width of the floor (m or mm)
b	breadth of the strongback (mm)
b_0	parameter for assessing v
$(EI)_B$	equivalent plate bending stiffness of the floor about an axis parallel to the joist direction (Nm^2/m)
$(EI)_{joist}$	flexural rigidity of the floor joist about an axis perpendicular to the beam direction (Nm^2/m), calculated as $(EI)_{joist} = E_{0,mean}\, I_y$
$(EI)_L$	equivalent plate bending stiffness of the floor about an axis perpendicular to the joist direction (Nm^2/m) and $(EI)_L = E_{0,mean}\, I_y / s$
E_{mean}	mean elastic modulus of timber materials (N/m^2 or N/mm^2)
E_0	elastic modulus parallel to the grain of the floor joist (N/m^2 or N/mm^2)
$E_{0,mean}$	mean value of the elastic modulus parallel to the grain of the floor joist (N/m^2 or N/mm^2)
F	unit point load, F = 1 kN
$f_{i,j}$	vibrational frequency for i^{th}-order and j^{th}-mode (Hz)
f_1	fundamental frequency for Mode 1-1 (Hz)
h	depth of the strongback (mm)
I_y	second moment of area about the major axis of the floor joist (m^4)
k_{amp}	amplification factor to account for shear deflections

k_{dist} factor to account for proportion of point load distributed to adjacent joists by floor decking

k_{strut} factor to account for strutting

L span of the floor (m or mm)

L_{eq} equivalent floor span (m or mm)

m mass of the timber floor per unit area (kg/m^2)

m_0 mass of the trolley (kg)

m' equivalent total mass due to the trolley (kg/m^2)

m_0' equivalent mass due to the trolley (kg/m^2)

n number of stronbacks

n_{40} number of first-order modes with natural frequencies up to 40 Hz

s joist spacing of the floor (m or mm)

t thickness of the floor deck or roof ceiling (mm)

v unit impulse velocity (m/Ns^2)

VDV_b vibration dose value for vertical vibrations

VDV_d vibration dose value for horizontal vibrations

V_{max} maximum vibration strength

v_{rms} root-mean-square velocity

$v_{w,95}$ 95% fractile weighted velocity

W weight of the joist (kg)

w maximum instantaneous vertical deflection under a unit vertical point load F at any point of the floor (mm/kN)

$\zeta_{i,j}$ damping ratio for ith-order and jth-mode

ζ_1 damping ratio for Mode 1-1

ρ_{mean} mean density of timber (kg/m^3)

1. Introduction

Recently metal web timber joists have been largely used to replace traditional solid timber joists and other engineered joists for constructing floors in low-rise residential houses and long-span floors in commercial buildings. The lightness of timber flanges with the strength of strut steel webs and span far large distances provides more design freedom for both floors and roofs in domestic, industrial and commercial buildings. The metal web joists produced by MiTek Industries Ltd., also called Posi-Joists, are effectively designed using commercial software for constructing floors and roofs (MiTek Industries Ltd, 2012). Top and bottom chords of such joists in the UK are normally manufactured from TR26 solid timber (BSI, 2002), with a height of 47 mm and a width varying from 72 mm to 122 mm, forming a series of standard joists (PS8 to PS16 Posi-Joists). Typical joist spacings are 400 mm and 600 mm. Two or three joists can be put at one location to stiffen and strengthen the floor (Figure 1). Strongbacks as bracings running perpendicular to the joists are often required to transfer the load to adjacent joists. Normally, one strongback is placed at mid-span or two at one-third spans.

In the UK, Eurocode 5 Part 1-1 or EC5-1-1 (BSI, 2004), together with the UK National Annex or UK NA (BSI, 2009), is widely used for design of timber floors constructed with metal web joists, including ultimate and serviceability limit state verifications. The ultimate limit states concern the safety of floor structures and verifications are checked against bending, shear, bearing and lateral stability. The serviceability limit states concern the functioning and appearance of floors under normal use and the comfort of people, and verifications are checked against deflection and vibration. Vibrational criteria often control the design of timber floors, in particular long span floors. The vibrational parameters include fundamental frequency, unit point load deflection and unit impulse velocity response.

In Europe and Canada, research was conducted on assessing the dynamic performance of timber floors and human perception. In the 1980s, Ohlsson (1982) investigated human-induced vibrations of timber floors, and proposed criteria for assessing human comfort by limiting the fundamental frequency, point load deflection and impulse velocity response. His work was adopted in EC5-1-1 for vibrational serviceability design of lightweight timber floors. Chui (1987) conducted field tests to evaluate timber floors using the root-mean-square acceleration (the r.m.s. acceleration) and suggested that the r.m.s. acceleration for design be less than 0.45 m/s^2. Hu (1992) simulated the dynamic behaviour of ribbed plates by considering shear deformation and rotatory inertia and well predicted the vibrational test results on lightweight I-joist floors. Eriksson (1994) investigated the low frequency forces caused by human activities and developed frequency-domain models based on laboratory measurements. Smith (2003) summarised the serviceability aspects for timber floor vibrations, including human perception of motion, floor response to dynamic loading, avoidance of vibration problems and prediction of floor vibration. Toratti and Talja (2006) announced large dependence of disturbance on various vibration sources and proposed body perception scales. Labonnote (2012) studied the damping in timber materials and structures and classified the total damping into material and structural parts. Zhang et al. (2013) summarised current design regulations for comfort assessment of timber floor vibrations in Europe and illustrated design cases of timber floors constructed with solid joists, I-joists and metal web joists. Research work was also conducted in the UK. Zhang et al. investigated the vibrational serviceability performance of timber floors constructed from solid timber joists, I-joists and other engineered joists (Zhang, 2004; Zhang *et al.*, 2005; Bahadori-Jahromi *et al.*, 2006a, 2006b, 2007). Weckendorf et al. studied the vibrational performance of timber floors constructed with I-joists (Weckendorf et al., 2008a, 2008b, 2010; Weckendorf, 2009). Two technical books were also published on timber structural design to Eurocode (McKenzie and Zhang, 1987; Porteous and Kermani, 2012).

Comprehensive study is conducted on the dynamic response of timber floors on behalf of the Metal Web Working Group, comprising ITW Alpine, Gang Nail Systems, MiTek Industries Ltd and Wolf Systems (Zhang *et al.*, 2010). The investigation aims to assess the effects of joist spacing, strongback bracings and ceiling on the dynamic response of the timber floors constructed with metal web joists so as to evaluate the vibrational design criteria given by EC5-1-1 and the UK NA. The vibrational serviceability performance parameters studied include modal frequencies, in particular the fundamental frequency, modal damping, modal shapes and deflection under unit point load. This paper presents the experimental parts of the investigation and compares with the predicted results using the formulas given in EC5-1-1 and the UK NA.

2. Experimental programme

2.1 Floor configurations

Nine floor configurations (Floors A to I) are adopted for this test series, with variations of joist spacing, type, size, number and location of strongbacks, and roof ceiling, see Table 1.

2.2 Floor construction

All the floors are constructed with WOLF Easi-Joists (PS10) with an overall length of 5.25 m. TR26 solid timber of 47 mm × 97 mm is used for top and bottom chords and MS250 steel used for webs, giving an overall depth of 254 mm. The mean elastic modulus $E_{0,mean}$ parallel to the grain for TR26 solid timber chords is determined as 10784 N/mm^2, close to 11000 N/mm^2 given in BS 5268-2 (BSI, 2002). The mean density of TR26 solid timber for the chords, ρ_{mean}, is 468.46 kg/m^3, close to 450 kg/m^3 given by the manufacturers. The average weight of the joists is 28.11 kg. The deck is formed with 22 mm T&G P5 chipboard sheets of 2400 mm × 600 mm fixed to the metal web joists and to the end bracings, with 8g × 50 mm Twinquik Plusdrive steel woodscrews at 300 mm centres. The mean density of the chipboard sheets, ρ_{mean}, is 621.84 kg/m^3. The C16 timber end bracings of 47 mm × 222 mm are fixed to both ends of the metal web joists and save cutting noggings between the joists. The C16 solid timber noggings of 47 mm × 72 mm are fixed to the joists using Cullen UZ/47 clips and 3.75 mm × 30 mm square twist nails. The 12.5 mm Gyproc wallboard ceiling sheets are fixed to the joists and noggings with Gyproc screws at 150 mm centres along the perimeter of the sheets and at 230 mm centres where ceiling crosses internal joists. The density of the wallboard sheets is 651.39 kg/m^3. The material, size and location of the strongbacks vary with the tests but those strongbacks are fixed to the noggings (Figure 2). The C16 solid timber noggings of 47 mm × 72 mm are fixed to both chords with 5.0 mm × 100 mm Speed-Drive steel woodscrews. The strongback is then fixed to the noggins, also tightly against the underside of the top chord, with 3 no 5.0 mm × 100 mm Speed-Drive steel woodscrews. Table 2 lists the material properties of the adopted strongbacks measured by Wolf System Ltd.

The tested floors are fixed onto the supporting structures at both ends, forming an effective span of 5.15 m, which are manufactured by Donaldson Timber Engineering and comprise two 2-ply TR26 chord girder walls of 1.2 m × 5.0 m and ten 45° triangular outriggers, 5 for each end. The top chords of the walls are manufactured from 47 mm × 147 mm solid timber and the bottom chords and bracings are from 47 mm × 72 mm solid timber. The outriggers have a cross-section of 35 mm × 72 mm. All the chord girder walls and outriggers are directly connected to the concrete floor. Figure 3 shows a typical metal web joist floor (Floor F).

2.3 Vibrational performance testing

Figure 4 shows the equipment used for vibrational testing. A grid of 5 × 5 = 25 equally distributed node points is drawn on the floor surface served as measurement points and is mirrored in the ARTeMIS Testor software on the laptop screen, used for controlling the vibration tests. Five roving sensors are used to cover all 25 measurement points through 5 measurements. Two additional sensors are placed as references at two pre-fixed locations to capture all vibration modes of interest. The dynamic testing consists of an output-only modal analysis, which is carried out on all metal web joist floors to obtain modal frequencies, damping ratios and modal shapes.

The floor is excited using a 5.0 kg trolley, including a squared wooden board, four small plastic wheels and a long wooden handle, and loaded with coarse aggregates. During the testing, the trolley is pushed up to the centre of the floor from the edge and pulled back while moving it from one side to other side of the floor, until the floor area is fully excited. The time duration for each measurement is 100 seconds. The accelerometers transform vertical vibrational movements into electrical signals, which are recorded by the data recorder. The recorded signals are then processed using two embedded ARTeMIS Extractor software: the Enhanced Frequency Domain Decomposition (EFDD) and the Stochastic Subspace Identification (SSI). In the EFDD the signals are processed by a Fast Fourier Transform (FFT) to obtain the spectral densities in the frequency domain and an inverse FFT is applied to the densities for estimating modal parameters, while in the SSI a time domain approach is used. Those results obtained by the SSI are presented here due to smaller variations on the studied parameters. Further information on the SSI is given by Brincker and Andersen (2006) and Peeters and De Roeck (2001). From this analysis, modal frequencies, modal damping ratios and modal shapes are obtained.

2.4 Unit point load deflection testing

All floors are tested to measure the deflection under 1 kN at mid-span of each joist in turn. The equipment used for the point load deflection tests contain LVDTs (Linear Voltage Displacement Transducers) (Figure 5(a)), steel weights, hanger and base plate (Figure 5(b)), and data recorder. The total weight applied is 101.94 kg (1.0 kN). The data recorder is the 20-channels Instrument Division System 5000, Model 5100 Scanner. Each floor is loaded at mid-span of each joist over an area of 100 mm × 100 mm using the steel plate. The mid-span deflections are measured using the LVDTs for all joists when each of them is loaded. Thus, nine LVDTs are used for Floors A to F and thirteen LVDTs for Floors G to I. Because of limited LVDTs (up to 15), only six LVDTs are used to measure the deflections at supports for Floors A to F, placed at both support ends of Joists 1, 5 and 9 (the most outer joists and central one). Only two LVDTs are used for Floors G to I, movably placed at both support ends of each loaded joist. All LDVTs are 350 Ω full bridge transducers with an input of 10V AC/DC, and are calibrated before the deflection tests. All other unmeasured deflections at the support ends of the joists are determined using linear interpolations. Each set of measurements is repeated twice to obtain reliable results.

3. Vibrational test results and discussion

Table 3 presents the vibrational test results of all first-order modal frequencies up to 40 Hz and damping ratios. A first-order mode implies only a half sine wave along the floor span direction. The first subscripts for the frequency *f* and the damping ratio ζ represent the number of half sine waves in the floor span direction and the second subscripts represent the number of half sine waves in the transverse direction (along the support direction). In EC5-1-1, a parameter n_{40}, the number of first-order modes with natural frequencies up to 40 Hz, is defined for calculating the unit impulse velocity *v,* and the measured n_{40} values are also listed in Table 3. The smaller the n_{40} value, the better the vibrational performance of the floor. Table 4 lists the frequencies up to 40 Hz of the second-order modes and damping ratios. The frequencies in the brackets imply those slightly over 40 Hz. The mean values and standard deviations for the damping ratios are also given in the tables. Figure 6 shows the first-order mode shapes of Floor I, and Figure 7 shows the corresponding second-order mode shapes. The floor span and support line directions, noted as *L* and *T*, are shown in the figures to help understand these mode shapes.

3.1 Fundamental frequency

3.1.1 Joist spacing

The comparison of the modal frequencies for three sets of floors (Floors A and G; Floors E and H; Floors F and I) with the same configurations but different joist spacings (600 mm and 400 mm) shows an increase in the first two modal frequencies for the smaller spacing. In particular the increment for the fundamental frequency (Mode 1-1) varies from 0.8 Hz to 1.1 Hz. For higher modes, the decrease in joist spacing slightly reduces the frequencies for the floors stiffened with strongback only or strongback and ceiling. In general, smaller spacing slightly raises the fundamental frequency as the increased stiffness overwhelms the increased mass.

3.1.2 Ceiling

The comparison of the modal frequencies for two sets of floors without or with ceiling (Floors E and F; Floors H and I) shows a decrease in the first two modal frequencies for the floors with ceiling due to the extra weight introduced. The increased stiffness due to the composite effect with ceiling does not compensate the weight increase. Drops of 1.1-1.2 Hz in the fundamental frequency are observed. For higher modes, the addition of the ceiling increases the frequencies and for Mode 1-6 an increase of up to 2.4 Hz can be observed.

3.1.3 Number, size and type of strongbacks

The comparison of the modal frequencies for two sets of floors (Floors A, E and D; Floors G and H) with different numbers of strongbacks shows that the increasing numbers of strongback little affects the first two frequencies but largely influences the higher frequencies. In particular, the use of two strongbacks increases the frequency of the floors with the 600 mm joist spacing by 4.7 Hz for Mode 1-4 and 10.1 Hz for Mode 1-5. Even one strongback can increase the frequency for Mode 1-6 by 10 Hz for the floors with different joist spacings. The comparison of the modal frequencies for one set of floors (Floors A, E and B) with different strongback sizes shows that the increasing strongback size has little effect on the first two frequencies but largely influences the higher frequencies. One 35 mm × 97 mm TR26 strongback put at mid-span raises the floor frequency with 600 mm joist spacing by 3.5 Hz for Mode 1-4 and 6.8 Hz for Mode 1-5. However, one 47 mm × 147 mm TR26 strongback at mid-span increases the frequency for Mode 1-5 by up to 13.4 Hz. Finally, the comparison of the modal frequencies for one set of floors (Floors B and C) with different types of strongback, i.e. 47 mm × 147mm TR26 solid timber and 45 mm × 147mm Kerto S laminated veneer lumber (LVL), shows similar dynamic behaviours because both strongbacks have similar sizes and stiffnesses. Little difference in frequency for all first-order modes is observed.

3.1.4 Comparison of the calculated fundamental frequencies to EC5-1-1 with the measured

In EC5-1-1, the fundamental frequency of residential floors is required to be larger than 8 Hz. For a rectangular floor with dimensions of $L \times B$, simply supported along all four edges, the fundamental frequency f_1 can be calculated from Equation 7.4 of the code as

1. $$f_1 = \frac{\pi}{2L^2}\sqrt{\frac{(EI)_{\mathrm{L}}}{m}}$$

where

$(EI)_L$ is the equivalent plate bending stiffness of the floor about an axis perpendicular to the joist (Nm^2/m) and is calculated as $(EI)_L = E_{0,mean}\, I_y / s$,

$E_{0,mean}$ is the mean value of the elastic modulus parallel to the grain of the floor joist (N/m^2),

s is the joist spacing of the floor (m),

I_y is the second moment of area about the major axis of the floor joist (m^4),

m is the mass of the timber floor per unit area (kg/m^2).

The above equation does not include the effect of the trolley with m_0 = 5 kg for exciting the floor. To reflect this, Rayleigh's approximation method (Tedesco et al., 1999; Humar, 2012) is used to modify Equation 1 by introducing an equivalent mass $m_0' = 2m_0/Ls$ (kg/m^2) due to the trolley. Here the deformed floor shape is assumed to be a half sine wave and the trolley is assumed to act at mid-span of the floor joist considered. Thus, the original floor mass m is modified using an equivalent total mass $m' = m + m_0'$, while the floor stiffness remains the same.

Table 5 lists the calculated fundamental frequency values based on Equation 1 using both m and m' for all floors, together with their ratios to the measured values. Figure 8 shows the calculated and measured fundamental frequencies for all floors. On average, the calculated fundamental frequency values, $f_{1,EC5}$, are 11% larger than those measured except Floor F with an error of 2.1%. However, the calculated fundamental frequency values, $f_{1,revised}$, based on the modified mass are only 4% larger. Actually Equation 1, deduced from beam bending theory, is applicable to floors simply supported along two edges like those tested here. Beside the trolley weight, the support structures may not be fully rigid, making the system less stiff and slightly reducing f_1. Figure 8 shows that all measured f_1 values are larger than 8 Hz, indicating that all nine floors are satisfactory with respect to f_1.

3.2 Damping

Damping is an intrinsic structural property of floors and represents the ability to absorb and dissipate kinetic energy. The higher the damping, the more rapidly the vibrational energy dissipates and the better a structure performs. Damping cannot be calculated but can only be determined through experimental testing. In this study, damping is investigated as a parameter for designing metal web joist floors for the serviceability criteria on unit impulse velocity specified in EC5-1-1, with more attention paid to the first-order modal damping ratios. Figure 9 shows the measured values of the Mode 1-1 damping ratio $\zeta_{1,1}$ or simply ζ_1 for all nine floors. There is no obvious trend between the measured ζ_1 values and the configuration parameters, indicating that ζ_1 is only dependent on the floor type. ζ_1 varies from 0.77% to 0.99% with an average of 0.86% and a standard deviation of 0.07%. This is less than 50% of the design value 2% recommended in the UK NA (BSI, 2004) and smaller than 1% recommended in EC5-1-1

(BSI, 2009). In contrast, previous study showed that ζ_1 for similar floors constructed with I-joists varied between 2% and 4% (Weckendorf, 2008a), much larger than those measured on the metal web joist floors. Table 3 also shows that the average damping ratios for Modes 1-2 and 1-3 are 0.82% and 0.94%, both below 1%. For Modes 1-4 to 1-6, the damping ratios vary from 1.18% to 1.28%, slightly larger than 1%. Table 4 shows that the average damping ratios for the first two second-order modes, Modes 2-1 and 2-2, are 1.73% and 1.86%, both below 2%.

In this investigation, an average damping ratio of 0.86% for ζ_1 is accurately measured for the tested metal web joist floors under lab conditions using the comprehensive testing facilities and sophisticated software. In practice, situations could be much worse due to variations in floor geometries, available testing facilities, utilised analysing software, etc., and also due to the difficulties in repeatability. Therefore a damping ratio of 0.9% or simply 1% is recommended for structural design and analysis of metal web joist floors.

3.3 Unit impulse velocity response

For timber floor design, the velocity response under unit impulse, *v*, is used to assess the vibrational serviceability performance. From Clause 7.3.3 in EC5-1-1, for residential floors with a fundamental frequency greater than 8 Hz, Equation 7.4 should be verified

2. $$v \leq b_0^{(f_1 \zeta - 1)}$$

where *v* (m/Ns^2), the maximum initial value of the vertical floor vibration velocity (m/s) caused by a unit impulse 1.0 Ns, can be determined from Equation 7.6 of EC5-1-1 as

3. $$v = \frac{4\,(0.4 + 0.6\,n_{40})}{m\,B\,L + 200}\ (\mathrm{m/Ns^2})$$

where

b_0 is a parameter for assessing *v* and can be determined from Figure 7.2 in EC5-1-1,

f_1 is the fundamental frequency and is obtained from Equation 7.4 in EC5-1-1 or Equation 1,

ζ is the damping ratio, recommended as ζ = 0.01 in EC5-1-1 and ζ = 0.02 in the UK NA.

The parameter n_{40} can be calculated from Equation 7.7 of EC5-1-1 as

4. $$n_{40} = \left\{ \left[\left(\frac{40}{f_1} \right)^2 - 1 \right] \left(\frac{B}{L} \right)^4 \frac{(EI)_\mathrm{L}}{(EI)_\mathrm{B}} \right\}^{0.25}$$

where $(EI)_B$ is the equivalent plate bending stiffness of the floor about an axis parallel to the beam (Nm^2/m), gained by superpositioning the individual stiffnesses according to the UK NA as

$$(EI)_{\mathrm{B}} = \frac{E_{0,\mathrm{mean,P5}}\, t_{\mathrm{P5}}^{3}}{12} + \frac{E_{\mathrm{plasterboard}}\, t_{\mathrm{plasterboard}}^{3}}{12} + \frac{E_{\mathrm{strongback}}\, b_{\mathrm{strongback}}\, h_{\mathrm{strongback}}^{3}}{12L} \quad (5)$$

Here, the symbol E stands for the elastic modulus, b for the breadth, t for the thickness and h for the depth, and the subscript P5 implies the P5 chipboards. The unit impulse velocity could not be directly measured, but Equation 3 shows that the rise in n_{40} always unfavourably leads to a larger v. The smaller the value of n_{40}, the smaller v and the better vibrational performance of the floor. Thus n_{40} can be indirectly used to assess the vibrational performance of a floor. Table 6 lists the calculated values of v and n_{40} for the floors with joist spacings of 600 mm (Floors A to F) and 400 mm (Floors G to I). The ratios of the unit impulse velocity v to the design limit $b^{(f_1 \zeta - 1)}$ are also included. When this ratio is larger than 1.0, the design will fail to pass the criterion.

The comparison of the calculated n_{40} values with the measured ones shows that the differences between them for all floors are less than one, indicating that Equation 7.7 of EC5-1-1 can well predict n_{40} so as to assess the vibrational performance of the floor. Compared with Floor A with 600 mm joist spacing and Floor G with 400 mm joist spacing, the measured and calculated results show that the use of strongbacks significantly reduces n_{40}. The stiffer the strongback, the lower n_{40} and the better vibrational performance of the floor (Floors B to E vs Floor A). The use of 47 mm × 147 mm TR26 solid timber (Floor B) and 45 mm × 147mm Kerto S LVL (Floor C) causes the lowest n_{40}. The measured n_{40} decreases from 8 for the floor without strongbacks and ceiling, with 600 mm joist spacing (Floor A), to 5 (Floors B and C), down by 3. The use of ceiling together with strongbacks (Floors F and I) lowers the measured n_{40} from 8 to 6, down by 2. No difference is found in the measured n_{40} values for the floors with or without ceiling but with strongbacks (Floor E vs Floor F; Floor H vs Floor I). Larger number of strongbacks decreases the measured n_{40} (Floor D vs Floors E and A) but the larger joist spacing slightly increases the measured n_{40} (Floor A vs Floor G; Floor E vs Floor H; Floor F vs Floor I).

Figure 10 illustrates the calculated unit impulse velocities of all floors based on the calculated n_{40} values, together with the design limits in EC5-1-1 and the UK NA. The comparison shows that all floors satisfy the criteria for unit impulse velocity set in the UK NA and all floors satisfy the criteria set in EC5-1-1 except Floor A which has no strongbacks and ceiling and with 600 mm joist spacing. The results also show that the use of strongbacks can significantly reduce v. The stiffer the strongback, the lower v and the better vibrational performance of the floor (Floors B to E vs Floor A). The use of 47 mm × 147 mm TR26 solid timber (Floor B) and 45 mm × 147mm Kerto S LVL (Floor C) shows the largest reduction in v, down from 0.0238 m/Ns^2 to 0.0137 m/Ns^2 and 0.0135 m/Ns^2 or down by 42.2% and 43.1%. The addition of the ceiling decreases v compared with the floors without or even with strongbacks (Floor F vs Floors A and E; Floor I vs Floors G and H). Larger number of strongbacks decreases v (Floor D vs Floors E and A). As expected, joist spacing also affects v. The smaller the joist spacing, the lower v (Floor A vs Floor G; Floor E vs Floor H; Floor F vs Floor I).

On the other hand, the design limit for unit impulse velocity given in the UK NA is very relaxed compared with that given in EC5-1-1 because the former adopts a higher damping ratio of 2%. In this investigation, however, an average damping ratio of 0.86% is observed for the tested metal web joist floors. Hence, a damping ratio of 1% given in EC5-1-1 may be a better option for the metal web joist floors, but the adoption of $\zeta = 1\%$ will tighten the design limit.

4. Unit point load deflection test results and discussion

Table 7 and Figure 11 illustrate the measured maximum displacements of all floors under 1 kN.

4.1 Joist spacing

For the same floor configuration, a reduction in joist spacing significantly lowers the maximum displacement w. For the floors without strongback and ceiling (Floors A and G), w decreases from 1.80 mm to 1.44 mm, down by 0.36 mm or 20%. For the floors with strongback but without ceiling (Floors E and H), w decreases from 1.25 mm to 0.96 mm, down by 0.29 mm or 23.2%. For the floors with strongback and ceiling (Floors F and I), w decreases from 0.97 mm to 0.86 mm, down by 0.11 mm or 11.3%, not as much as those for the floors without ceiling.

4.2 Ceiling

The introduction of ceiling largely enhances the floor stiffness and reduces the displacement. For the floors with 600 mm joist spacing (Floors E and F), w decreases from 1.25 mm to 0.97 mm, down by 0.28 mm or 22.4%. For the floors with 400 mm joist spacing (Floors H and I), w decreases from 0.96 mm to 0.86 mm, down by 0.10 mm or 10.4%, not as significant as those with 600 mm joist spacing.

4.3 Number, size and type of strongbacks

The use of strongbacks significantly enhances the floor stiffness and lowers the maximum displacement. For the floors with 600 mm joist spacing (Floors A, E and D), w decreases from 1.80 mm to 1.25 mm for the floor with one strongback at mid-span (Floor E) and to 1.28 mm for the floor with two strongbacks at third-spans (Floor D), down by 0.55 mm and 0.52 mm or 30.5% and 28.9%, indicating that the enhancing effectiveness of stiffness largely depends on the location the strongback situates. The nearer the strongback is to mid-span, the more effective the stiffness enhancement. For the floors with 400 mm joist spacing (Floors G and H), w decreases from 1.44 mm to 0.96 mm, down by 0.48 mm or 33.3%. The increase in the strongback size greatly enhances the floor stiffness and lowers w when the strongbacks are placed at the same location. For the floors with 600 mm joist spacing (Floors A, E and B), w decreases from 1.80 mm to 1.25 mm for the floor with a TR26 strongback of 35 mm × 97 mm at mid-span (Floor E) and to 1.11 mm for the floor with a TR26 strongback of 47 mm × 147 mm at mid-span (Floor B), down by 0.55 mm and 0.69 mm or 30.5% and 38.3%. In this study, because two larger strongbacks have similar sizes and stiffnesses, little variation in w is expected, 1.11 mm Floor B versus 1.08 mm for Floor C.

4.4 Comparison of the calculated maximum displacements to EC5-1-1 and the UK NA with those measured

EC5-1-1 specifies that the deflection of the timber floor under 1 kN, w, should satisfy:

6. $$w \leq a$$

where

w is the maximum instantaneous vertical deflection under F = 1 kN (mm/kN),

a is the design limit of the deflection of the timber floor under F (mm/kN).

Using Equation NA.1 in the UK NA, the floor deflection, w, should be calculated as

7. $$w = \frac{1000\, k_{\text{dist}}\, L_{\text{eq}}{}^{3}\, k_{\text{amp}}}{48\,(EI)_{\text{joist}}} \quad \text{(mm/kN)}$$

where

k_{dist} is the factor to account for proportion of point load distributed to adjacent joists by floor decking, and is calculated as

$$k_{\text{dist}} = \max\left\{k_{\text{strut}}\left[0.38 - 0.08\ln[14\,(EI)_{\text{B}}/s^4]\right];\ 0.30\right\},$$

k_{strut} is a factor to account for strutting and k_{strut} = 0.97 for single or multiple lines of strutting otherwise k_{strut} = 1.0,

$(EI)_{\text{B}}$ is the equivalent plate bending stiffness of the floor about an axis parallel to the joist direction (Nm^2/m), calculated as $(EI)_{\text{B}} = E_{0,\text{mean,P5}}t^3/12$,

L_{eq} is the equivalent floor span (mm) and $L_{\text{eq}} = L$ for simply supported single span joists,

k_{amp} is an amplification factor to account for shear,

$(EI)_{\text{joist}}$ is the flexural rigidity of the floor joist about an axis perpendicular to the joist direction (Nm^2/m), calculated as $(EI)_{\text{joist}} = E_{0,\text{mean}}\, I_{\text{y}}$.

The UK NA to EC5-1-1 also recommends for $(EI)_{\text{B}}$:

- $(EI)_{\text{B}}$ is calculated as the flexural rigidity of the floor decking perpendicular to the joists, using E_{mean} for E.

- $(EI)_B$ may be increased by adding the flexural rigidity of plasterboard ceilings fastened directly to the soffit of the floor joists, assuming $E_{plasterboard}$ = 2000 N/mm^2.
- $(EI)_B$ may be increased for open web joists with a continuous transverse bracing member fastened to all the joists within 0.1L of mid-span, by adding the bending stiffness of the transverse member (Nmm^2) divided by the span L (m).

The design deflection limit for the timber floor under unit point load, a, can be determined based on Table NA.5 in the UK NA as

$$a = \begin{cases} 1.80 \text{ mm/kN} & \text{For spans} \leq 4000 \text{ mm} \\ 16500 / L^{1.1} \text{ mm/kN} & \text{For spans} > 4000 \text{ mm} \end{cases} \quad (8)$$

Table 7 also lists the calculated maximum displacements to Equation NA.1 of the UK NA for the metal web joist floors, together with the design limit a = 1.36 mm. Figure 11 shows the calculated w values for all floors. On average, the calculated values are only 2% larger than those measured. However, variations between the calculated and measured values are very large, from -16.1% (Floor G) to +31.1% (Floor F). There is no clear trend between the calculated and measured maximum displacements. Clearly, all the floors with strongbacks are adequate to the serviceability requirements except two floors without strongbacks, indicating for the current span, strongbacks are needed to evenly distribute the floor loading and lower w.

It should be pointed out that a good serviceability design of timber floors should also consider human perception of floor vibrations. For this purpose, various vibrational parameters have been proposed and the limits been set up, e.g. the root-mean-square velocity and acceleration, v_{rms} and a_{rms}, the 95% fractile weighted velocity and acceleration, $v_{w,95}$ and $a_{w,95}$, the maximum vibration strength V_{max}, the vibration dose values for vertical and horizontal vibrations, VDV_b and VDV_d, etc. A large damping in timber floors no doubt will lower the peak values of these parameters and help a satisfactory design. This has been extensively explored in another paper by the first author and researchers from other European countries (Zhang *et al.*, 2013).

5. Conclusions

Experimental investigations are conducted on the vibrational performance of nine metal web joist floors enhanced with strongbacks. Modal frequencies, modal damping ratios and unit point load displacements are measured and analysed for various joist spacing, number, size, location and type of strongbacks, and ceiling. The measured parameters are compared with the calculated ones based on EC5-1-1 and the UK NA.

Joist spacing, strongback bracings and ceiling do not largely influence the fundamental frequency but affect higher modal frequencies. All the tested floors have fundamental frequencies over 14 Hz which are greater than the design threshold of 8 Hz set in EC5-1-1.

Joist spacing, strongback bracings and ceiling do not largely influence the damping ratios of the lower modes. The damping ratio of the fundamental mode is measured as 0.86% on average, which is slightly below 1% recommended in EC5-1-1 and much smaller than 2% recommended in the UK NA. Therefore, the former may be a better design option for metal web joist floors. The value suggested in EC5-1-1 should only be taken if no other values could be found.

The increase in number and size of strongbacks largely decreases the number of first-order modes with natural frequencies up to 40 Hz, which in turn significantly decreases the unit impulse velocity and thus helps easier fulfilment of the velocity design criterion. Hence, strongbacks should be used to enhance the vibrational performances of timber floors, with respect to velocity response.

Joist spacing, strongback bracings and ceiling largely influence the maximum displacement of metal web joist floors under unit point load. The decrease in joist spacing, the increase in number and size of strongbacks, and the use of ceiling all significantly reduce the maximum displacement. On average, the calculated maximum displacements based on the equations given in the UK NA are close to those measured. All tested floors except one without strongback and ceiling, have the maximum displacements below the limit set by the UK NA.

Due to the limitations of time and cost, only nine floors are tested. Numerical simulations are being conducted at Glasgow Caledonian University on the effects of other geometric configurations on the vibrational serviceability performance of metal web joist floors and roofs, e.g. metal web joist sizes, more arrangements of strongbacks, various floor decks, etc., and the results will be reported when available.

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Table 1. Tested floors with various configurations

Floor	Joist spacing s (mm)	Strongback	Ceiling
A	600	None	None
B	600	47 mm × 147 mm TR26 solid timber at mid-span	None
C	600	45 mm × 147 mm Kerto LVL at mid-span	None
D	600	35 mm × 97 mm TR26 solid timber at one-third spans	None
E	600	35 mm × 97 mm TR26 solid timber at mid-span	None
F	600	35 mm × 97 mm TR26 solid timber at mid-span	Yes
G	400	None	None
H	400	35 mm × 97 mm TR26 solid timber at mid-span	None
I	400	35 mm × 97 mm TR26 solid timber at mid-span	Yes

Table 2. Material properties of the adopted strongbacks

Strongback	Reference number	Length L (mm)	Weight W (kg)	Stiffness E_0 (N/mm^2)	Density ρ (kg/m^3)
35 mm × 97mm TR26	1	4910	8.35	10810	482
35 mm × 97mm TR26	2	4910	8.40	11456	485
35 mm × 97mm TR26	3	4910	9.25	12625	534
35 mm × 97 mm TR26	4	4910	8.35	12057	482
47 mm × 147 mm TR26	5	4910	16.20	12669	460
45 mm × 147 mm Kerto S	6	4910	17.00	11200	492

Table 3. Frequencies and damping ratios of first-order modes for frequencies up to 40 Hz

Floor	$f_{1,1}$ (Hz)	$\zeta_{1,1}$ (%)	$f_{1,2}$ (Hz)	$\zeta_{1,2}$ (%)	$f_{1,3}$ (Hz)	$\zeta_{1,3}$ (%)	$f_{1,4}$ (Hz)	$\zeta_{1,4}$ (%)	
A	14.4	0.88	16.0	0.95	18.1	0.79	20.6	0.88	
B	14.6	0.83	16.2	0.70	21.2	1.08	28.4	1.03	
C	14.6	0.88	16.2	0.77	21.3	0.91	28.3	1.34	
D	14.5	0.87	16.2	0.80	20.1	0.85	25.3	1.15	
E	14.5	0.79	16.2	0.83	19.6	0.90	24.1	1.43	
F	13.4	0.99	15.5	0.85	19.8	0.83	25.1	1.38	
G	15.5	0.77	17.0	1.05	18.8	1.13	21.0	1.39	
H	15.5	0.94	17.0	0.73	19.9	1.01	24.0	1.11	
I	14.3	0.80	16.2	0.73	19.7	0.98	24.7	1.19	
Mean		0.86		0.82		0.94		1.21	
SD		0.07		0.11		0.12		0.19	
Floor	$f_{1,5}$ (Hz)	$\zeta_{1,5}$ (%)	$f_{1,6}$ (Hz)	$\zeta_{1,6}$ (%)	$f_{1,7}$ (Hz)	$\zeta_{1,7}$ (%)	$f_{1,8}$ (Hz)	$\zeta_{1,8}$ (%)	n_{40}
A	23.7	1.03	27.3	0.85	31.3	1.18	35.3	1.20	8
B	37.1	1.15	-	-	-	-	-	-	5
C	37.1	1.30	-	-	-	-	-	-	5
D	33.8	1.29	-	-	-	-	-	-	5
E	30.5	1.37	37.2	1.40	-	-	-	-	6
F	32.2	1.59	39.4	1.28	-	-	-	-	6
G	23.8	1.46	27.4	1.24	30.9	1.17	34.2	1.05	8
H	30.0	0.96	36.7	1.22	-	-	-	-	6
I	31.7	1.36	39.1	1.18	-	-	-	-	6
Mean		1.28		1.20		1.18		1.12	
SD		0.20		0.19		0.01		0.11	

Table 4. Frequencies and damping ratios of second-order modes for frequencies up to 40 Hz

Floor	$f_{2,1}$ (Hz)	$\zeta_{2,1}$ (%)	$f_{2,2}$ (Hz)	$\zeta_{2,2}$ (%)	$f_{2,3}$ (Hz)	$\zeta_{2,3}$ (%)	$f_{2,4}$ (Hz)	$\zeta_{2,4}$ (%)
A	34.2	1.73	37.2	1.86	39.1	1.19	-	-
B	35.2	1.93	37.7	1.41	(40.1)	1.03	-	-
C	35.2	1.63	38.0	1.50	(40.1)	1.56	-	-
D	34.8	1.45	37.6	1.23	(41.1)	1.15	-	-
E	35.5	1.70	37.7	1.60	40.0	1.43	-	-
F	31.7	1.77	33.5	1.40	36.6	1.24	39.8	1.51
G	37.9	1.84	(40.7)	1.14	-	-	-	-
H	38.1	1.68	(40.6)	1.11	-	-	-	-
I	34.6	2.68	37.6	1.40	39.6	1.60	(42.3)	0.79
Mean		1.73		1.86		1.19		1.15
SD		0.35		0.24		0.22		-

Table 5. Comparison between the calculated and measured fundamental frequencies

Floor	A	B	C	D	E	F	G	H	I
L (mm)	5150	5150	5150	5150	5150	5150	5150	5150	5150
B (mm)	4900	4900	4900	4900	4900	4900	4900	4900	4900
s (mm)	600	600	600	600	600	600	400	400	400
$I_{y,joist}$ ($\times 10^6$ mm^4)	99.353	99.353	99.353	99.353	99.353	99.353	99.353	99.353	99.353
$E_{0,mean,TR26}$ (N/mm^2)	0	10784	10784	10784	10784	10784	0	10784	10784
m (kg/m^2)	23.850	24.415	24.477	24.438	24.176	33.290	28.369	28.671	37.782
m' (kg/m^2)	27.086	27.651	27.713	27.674	27.412	36.526	33.223	33.525	42.636
$(EI)_{joist}$ (MNm^2)	1.0714	1.0714	1.0714	1.0714	1.0714	1.0714	1.0714	1.0714	1.0714
$(EI)_L$ (MNm^2/m)	1.7857	1.7857	1.7857	1.7857	1.7857	1.7857	2.6786	2.6786	2.6786
$f_{1,EC5}$ (Hz)	16.2	16.0	16.0	16.0	16.1	13.7	18.2	18.1	15.8
$f_{1,revised}$ (Hz)	15.2	15.1	15.0	15.0	15.1	13.1	16.8	16.7	14.8
$f_{1,measured}$ (Hz)	14.4	14.6	14.6	14.5	14.5	13.4	15.5	15.5	14.3
$f_{1,EC5} / f_{1,measured}$	1.13	1.10	1.10	1.10	1.11	1.02	1.17	1.17	1.10
$f_{1,revised} / f_{1,measured}$	1.06	1.03	1.03	1.03	1.04	0.98	1.08	1.08	1.03

Table 6. Calculated unit impulse velocities for all nine tested floors

Floor	A	B	C	D	E	F	G	H	I
t_{deck} (mm)	22	22	22	22	22	22	22	22	22
$t_{plasterboard}$ (mm)	0	0	0	0	0	12.5	0	0	12.5
$b_{strongback}$ (mm)	0	47	45	35	35	35	0	47	45
$h_{strongback}$ (mm)	0	147	147	97	97	97	0	147	147
$n_{strongback}$	0	1	1	2	1	1	0	1	1
$I_{deck\ (b=1000mm)}$ (×10^6 mm^4)	0.8873	0.8873	0.8873	0.8873	0.8873	0.8873	0.8873	0.8873	0.8873
$I_{plasterboard}$ (×10^6 mm^4)	0	0	0	0	0	0.1628	0	0	0.1628
$I_{strongback}$ (×10^6 mm^4)	0	12.441	11.912	5.3239	2.6620	2.6620	0	2.6620	2.6620
$E_{mean,P5}$ (N/mm^2)	3000	3000	3000	3000	3000	3000	3000	3000	3000
$E_{plasterboard}$ (N/mm^2)	2000	2000	2000	2000	2000	2000	2000	2000	2000
$E_{0,mean,strongback}$ (N/mm^2)	0	11200	12669	11133	12625	12625	0	12057	12057
$\rho_{mean,P5}$ (kg/m^3)	621.84	621.84	621.84	621.84	621.84	621.84	621.84	621.84	621.84
$\rho_{mean,plasterboard}$ (kg/m^3)	651.39	651.39	651.39	651.39	651.39	651.39	651.39	651.39	651.39
$(EI)_{deck}$ (Nm^2/m)	2.662	2.662	2.662	2.662	2.662	2.662	2.662	2.662	2.662
$(EI)_{plasterboard}$ (kNm^2/m)	0	0	0	0	0	0.326	0	0	0.326
$(EI)_{strongback}$ (kNm^2/m)	0	27.057	29.303	11.509	6.526	6.526	0	6.232	6.232
$(EI)_B$ (kNm^2/m)	2.662	29.719	31.965	14.171	9.188	9.513	2.662	8.894	9.220
b_0	105.48	105.48	105.48	105.48	105.48	105.48	105.48	105.48	105.48
$n_{40,calculated}$	7.3	4.0	3.9	4.8	5.4	5.8	7.5	5.6	6.0
$n_{40,measured}$	8	5	5	5	6	6	8	6	6
v (m/Ns^2)	0.0238	0.0138	0.0135	0.0161	0.0179	0.0150	0.0214	0.0162	0.0139
ζ_{EC5}	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
$\zeta_{UK\ NA}$	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
$\zeta_{measured}$	0.0088	0.0083	0.0088	0.0087	0.0079	0.0099	0.0077	0.0094	0.0080
$b^{(f_1\zeta-1)}$ (EC5-1-1) (m/Ns^2)	0.0202	0.0200	0.0200	0.0200	0.0201	0.0180	0.0221	0.0220	0.0198
$b^{(f_1\zeta-1)}$ (UK NA) (m/Ns^2)	0.0429	0.0422	0.0421	0.0421	0.0425	0.0340	0.0517	0.0512	0.0412
$b^{(f_1\zeta-1)}$ (measured) (m/Ns^2)	0.0171	0.0167	0.0172	0.0171	0.0162	0.0176	0.0166	0.0187	0.0161
$\lambda_{v,EC5}$	1.18	0.69	0.68	0.81	0.89	0.84	0.97	0.74	0.70
$\lambda_{v,UK\ NA}$	0.55	0.33	0.32	0.38	0.42	0.44	0.41	0.32	0.34
$\lambda_{v,measured}$	1.39	0.825	0.79	0.95	1.10	0.85	1.29	0.87	0.86
Remarks on $\lambda_{v,EC5}$	Fail	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
Remarks on $\lambda_{v,UK\ NA}$	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
Remarks on $\lambda_{v,measured}$	Fail	Pass	Pass	Pass	Fail	Pass	Fail	Pass	Pass

Table 7. Comparison between the calculated and measured maximum displacements

Floor	A	B	C	D	E	F	G	H	I
L_{eq} (mm)	5150	5150	5150	5150	5150	5150	5150	5150	5150
k_{dist}	0.480	0.300	0.300	0.336	0.369	0.366	0.350	0.300	0.300
k_{amp}	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
k_{strut}	1	0.97	0.97	0.97	0.97	0.97	1	0.97	0.97
$(EI)_{joist}$ (×10^{12} Nmm^2/m)	1.0714	1.0714	1.0714	1.0714	1.0714	1.0714	1.0714	1.0714	1.0714
$(EI)_{b,eff}$ (×10^{9} Nmm^2/m)	2.6620	29.719	31.965	14.171	9.1877	9.5132	2.6620	8.8941	9.2196
$w_{calculated}$ (mm/kN)	1.66	1.04	1.04	1.16	1.28	1.27	1.21	1.04	1.04
$w_{measured}$ (mm/kN)	1.80	1.11	1.08	1.28	1.25	0.97	1.44	0.96	0.86
a (mm/kN)	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36
$w_{calculated} / a$	1.215	0.760	0.760	0.850	0.935	0.928	0.887	0.760	0.760
$w_{measured} / a$	1.318	0.811	0.789	0.936	0.918	0.708	1.057	0.707	0.631
Remarks on $w_{calculated} / a$	Fail	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
Remarks on $w_{measured} / a$	Fail	Pass	Pass	Pass	Pass	Pass	Fail	Pass	Pass

Figure 1. Applications of metal web joists for constructing floors (PS09 Posi-Joists)

(a) 45 mm × 147 mm Kerto S strongback at mid-span in Floor C

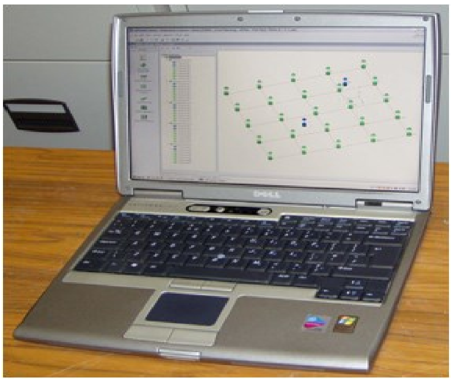
(b) 35 mm × 97 mm TR26 strongbacks at one-third spans in Floor D

Figure 2. Typical floors stiffened with strongbacks

Figure 3. A typical metal web joist floor of 5.15 m × 5.0 m (Floor F)

(a) TEAC data recorder

(b) Pinocchio vibraphone accelerometer



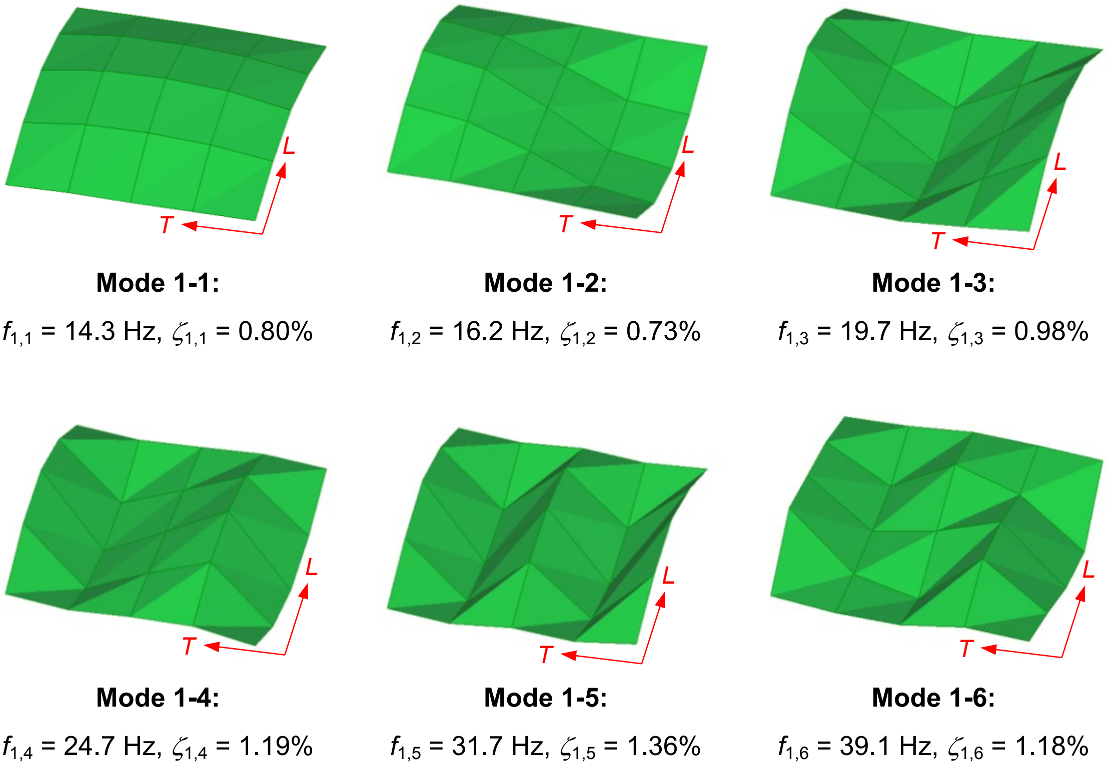
(c) Laptop with modal analysis software package

(d) Trolley with the attached weight

Figure 4. Equipment used for vibrational performance testing

(a) LVDT **(b)** Steel plates

Figure 5. Test equipment for measuring deflections under unit point load



Mode 1-1: $f_{1,1}$ = 14.3 Hz, $\zeta_{1,1}$ = 0.80%

Mode 1-2: $f_{1,2}$ = 16.2 Hz, $\zeta_{1,2}$ = 0.73%

Mode 1-3: $f_{1,3}$ = 19.7 Hz, $\zeta_{1,3}$ = 0.98%

Mode 1-4: $f_{1,4}$ = 24.7 Hz, $\zeta_{1,4}$ = 1.19%

Mode 1-5: $f_{1,5}$ = 31.7 Hz, $\zeta_{1,5}$ = 1.36%

Mode 1-6: $f_{1,6}$ = 39.1 Hz, $\zeta_{1,6}$ = 1.18%

Figure 6. First-order mode shapes of a typical floor (Floor I)

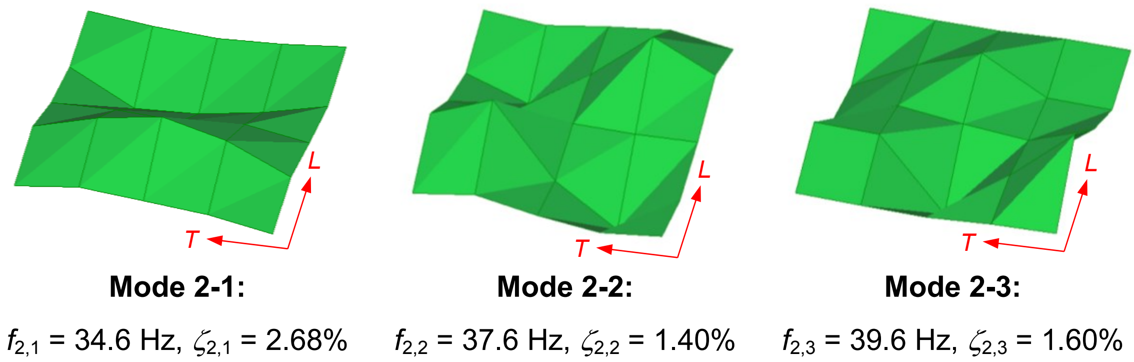


Figure 7. Second-order mode shapes of a typical floor (Floor I)

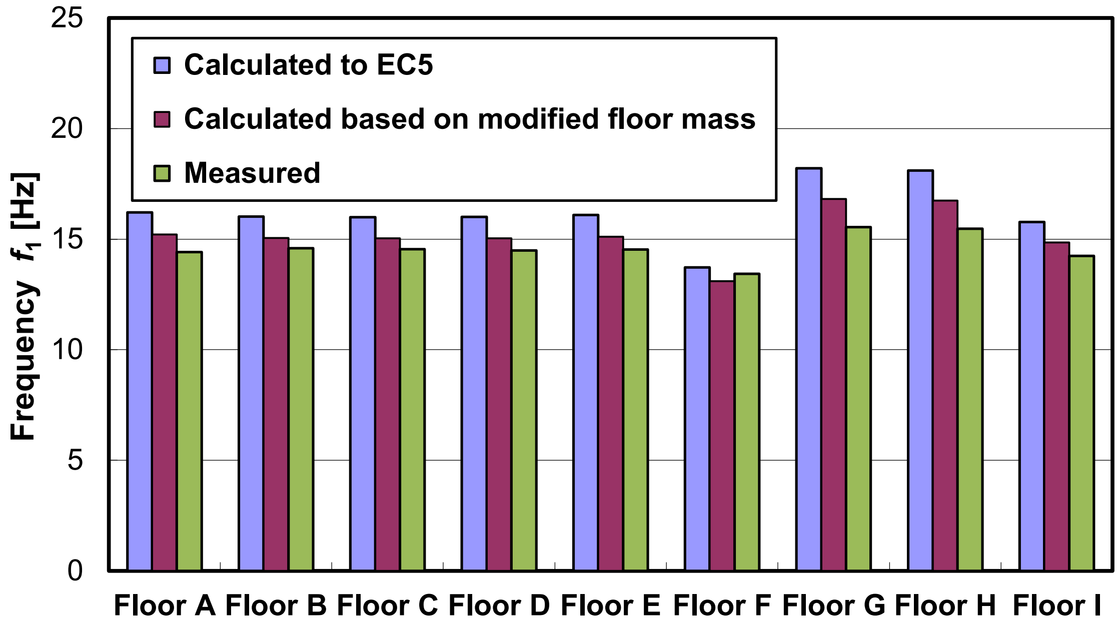


Figure 8. Fundamental frequencies calculated and measured for all tested floors

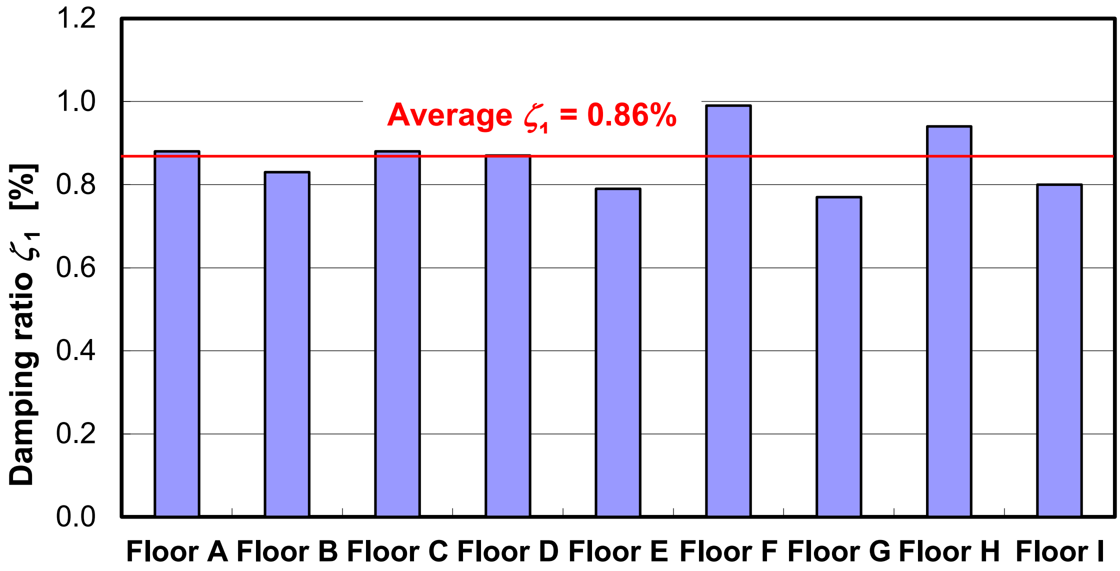


Figure 9. Measured Mode 1-1 damping ratio ζ_1 for metal web joist floors

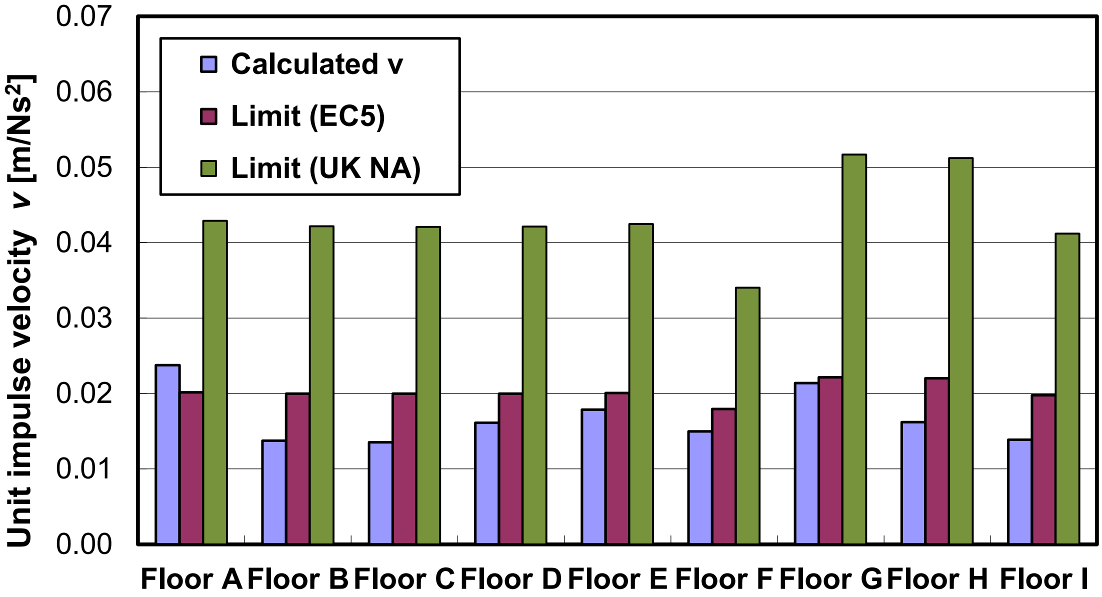
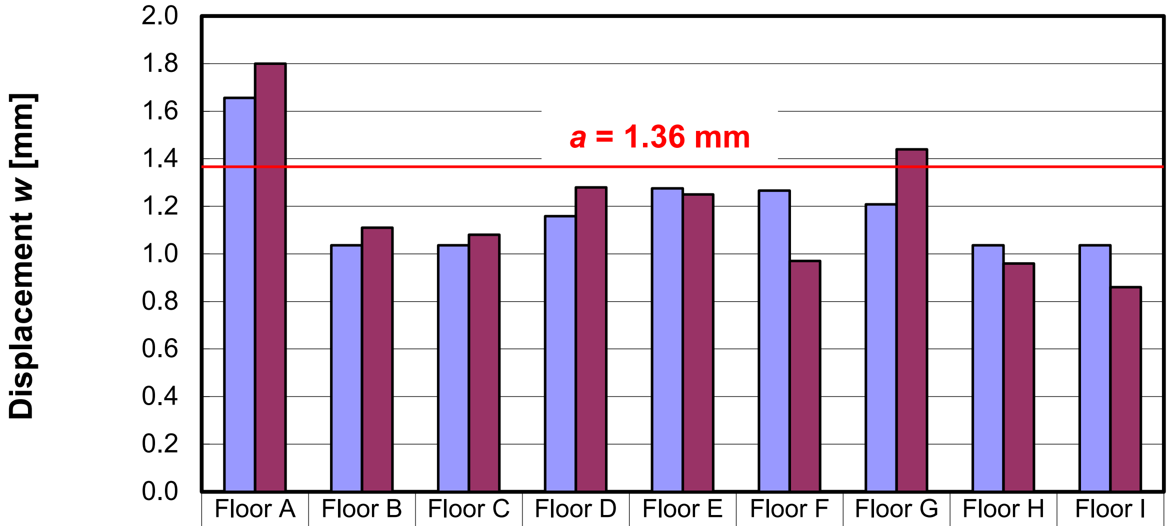


Figure 10. Calculated unit impulse velocities of tested floors and the recommended design limits in EC5-1-1 and the UK NA to EC5-1-1



	Floor A	Floor B	Floor C	Floor D	Floor E	Floor F	Floor G	Floor H	Floor I
Calculated	1.66	1.04	1.04	1.16	1.27	1.27	1.21	1.04	1.04
Measured	1.80	1.11	1.08	1.28	1.25	0.97	1.44	0.96	0.86

Figure 11. Measured and calculated maximum displacements under 1 kN point load for all tested floors